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A HALF MEGAWATT PULSE FORMING NETWORK (PFN).(U)

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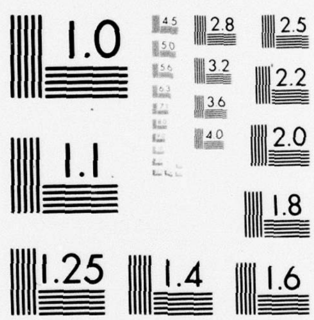

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A HALF MEGAWATT PULSE FORMING NETWORK (PFN)

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A lightweight half megawatt average power pulse forming network (PFN) designed to store 4 kilojoules (kJ) at 40 kilovolts has been developed. The energy storage system produces a 10 microsecond pulse at a repetition rate of 125 hertz and has a one ohm impedance. It is designed to operate adiabatically for durations of 60 seconds. A lifetime capability of over 4×10^5 pulses has been demonstrated.

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A HALF MEGAWATT PULSE FORMING NETWORK (PFN)

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ABSTRACT

A lightweight half megawatt average power pulse forming network (PFN) designed to store 4 kilojoules (kJ) at 40 kilovolts has been developed. The energy storage system produces a 10 microsecond pulse at a repetition rate of 125 hertz and has a one ohm impedance. It is designed to operate adiabatically for durations of 60 seconds. A lifetime capability of over 4 X 10^5 pulses has been demonstrated.

Discussion

Introduction

The objective specifications for the half megawatt pulse forming network (PFN) are given in Table I.

The requirements are not exceptional but what makes it interesting is the combination of repetition rate, life, temperature, and weight; especially the weight and getting it all to weight in at 100 pounds, constitutes a challenge.

The problem essentially is one of maximizing mean-power (mass) density - while keeping a rein on size, since high volume density is also a requirement, albeit a lesser one.

A PFN comprises capacitors, inductors, and some sort of structure. Aside from the routine determination of appropriate circuit constants, we must ensure that the inductors do not melt or fatigue; that the capacitors do not break down electrically or burst; and that external flashover does not happen - even in the elevated temperature (reduced number density) of the air surrounding the hot inductors.

TABLE I

Specifications

Voltage	40 kV maximum
Energy	4 kJ at 40 kV
Impedance	1 ohm
Reversal	20 percent
Pulse length	10 μs (nominal)
Rise time	1 μs (10-90 percent)
Fall time	2 μs (90-10 percent)
Ripple	± 5 percent
Pulse repetition rate	125 Hz
Number of pulses per burst	4,688 maximum
Burst duration	30 - 75 seconds
Ambient temperature	65°C maximum
Life (99.5% reliability)	$>10^5$ @ 65°C*
	$>10^6$ @ 20°C*
Weight	45 kg*

* These numbers are design goals.

Inductors

In a 30-second burst the coils behave largely adiabatically. On a purely adiabatic model the material criterion turns out quite simply to be $s/\rho^{1/2}$ (where s is the heat capacity per unit weight, and ρ is the electrical resistivity). We can, therefore, grade likely materials according to this criterion as shown in Table II.

TABLE II

Figure of merit for PFN coil materials

cal gm^{-1} $(cm\Omega)^{-1/2}$

berylium	250
berylium alloy	230
aluminum	130
magnesium	120
aluminum alloy (6061-76)	115
magnesium alloy (ZE 10 A-H24)	110
copper	74
silver	46

Obviously we choose berylium - until we discover the cost, then we start thinking about two-component systems for which, of course, we have two *figures of* merit: one for the conductor and the other for the heat reservoir (it is not a heat sink). The first is the same as in Table II, the second would be water - were it not for the high vapor pressure. We have experimented with a glycol/water mixture, which

worked very well until a fabrication defect caused a leak - which tended to put liquids in disfavor. Liquids, in fact, are inconvenient for another reason, viz., the varying heat deposition along the length of the coil: the front section carries current throughout the entire pulse, while the rear section is only active for about 20 percent of the pulse le gth. For minimum weight, therefore, we should grade the heat-reservoir mass according to the section position, which is difficult to do with liquids; tubing with tailored wall thickness would be ideal, but, in practice, loading the tube (before coiling) with a tapering bundle of aluminum wire gives a fair approximation to the ideal.

From a weight-saving point of view, the hotter we run the coil the better: less mass is needed to absorb the heat and there is more cooling during the pulse (less adiabaticity) resulting in less heat to be absorbed. Naturally, limits are set by the properties of the coil material or the proximity of other components. But the principal concern is to prevent the capacitor terminals rising above about 100°C. To avoid the heavy weight penalty of such a cool coil, we devised a thermal-insulator-electrical-conductor to connect the coil to the capacitor: it consists of a stub of large-diameter, thin-walled tubing filled with water; in addition, we can decrease the wire loading in these coil turns remote from the connection point.

The single-shot mechanical forces on the coil are not severe because the momentum pulse is modest; but severe vibration can build up in repetitive operation. Such vibration can be devastating to the internal capacitor connections, and to control this we have resorted to a snubbing clamp gripping the coil connections as shown in Figure 1.

Capacitors

Capacitors have rarely hitherto been required to run in bursts of high mean power with minimum weight. Thus, the design constraints are totally different from the usual ones such as cost/J-shot, inductance, peak current capability, failure distribution, power factor, shape, etc., more or less depending upon the application. Capacitor design is still more of an art than a science, and a variety of likely materials in various combinations were studied under the subject duty conditions. A grand total of 49.8 million shots have been accumulated on typical (50 to 100 joule) test samples to date.

It was discovered during this exercise that performance was often better at 65°C than at 20°C. This behaviour is quite anamalous, it had never been seen in previous capacitor applications. It led us to the hypothesis that failure resulted from poisoning by the concentration of corona-degraded by-products which do not have time to dissipate as they would in a conventional operating mode where the generation rate is low. We therefore evolved designs in which pockets for gas trapping were minimized, and we included additives to neutralize the by-products. In the result, our best design exhibited test lives

of over 4.10^6 shots, of which approximately one million were at an effective energy density of 13 J/kg and three million at an effective energy density of 19 J/kg with single failure (out of 16 samples) at 1.4×10^6 shots. (The effective energy density refers to the full-size PFN capacitor: the energy density in the samples was less because of the poorer volume/case ratio with smaller units.) At this point the capacitors were refilled with fresh impregnant and tests continued at an effective energy density of 23 J/kg. Re-impregnating capacitors is not recommended; it was done in this case to obtain some hint of the life/energy-density capability of this design without the expense and delay of making brand new samples (the old ones at four million shots were accumulating data at a tediously negligible rate.) These refurbished samples failed over the range 219,000 to 693,000 shots; virgin samples might be expected to perform even more attractively.

Structure

The capacitor cases constitute the bulk of the structure. Polypropylene brackets welded on to the top and bottom corners of the plastic cases were used to tie the capacitors to 1.25 cm diameter epoxy-fiberglass rods, and further support was provided by the snubbing clamp along the coil connections. The structure weight (excluding the capacitor cases themselves) amounted to less than 4 percent of the total weight.

PFN Performance

Six half size, 2 kilojoule 2 ohm PFNs, and two full size 4 kJ 1 ohm PFNs have been manufactured at Maxwell and then tested at ECOM. The 4 kJ PFN, shown in Figure 1, is 88 cm long X 45 cm wide and weighs 50 kg total. The evaluation was conducted in a dc resonant charging circuit having a 1.4 henry choke, and a hold-off diode. The dc power supply is rated at 37 kilovolts and 40 amperes average current. A resistive load made from a series parallel arrangement of ohmweave resistors was used. Various switches were used including the MAPS 250, MAPS 80, MAPS 40, KU 375, CH 1222 thyratron and an experimental cross field closing device. Pulse burst durations of 5, 15, 30, and 60 seconds were used in the evaluation. Off-times of from one to four and a half minutes were used in a somewhat random fashion depending on the ambient temperature of the capacitor cases which ranged from 20°C to 65°C.

Polypropylene dielectric and castor oil impregnate was used in four of the 2 kJ PFNs and polycarbonate and castor oil was used in two of the 2 kJ PFNs and both of the 4 kJ units. Average lifetime before failure for 7 capacitors of the 2 kJ polypropylene PFNs was 145,000 pulses. First capacitor failure on the 2 kJ polycarbonate PFN occurred at 800,000 pulses. To date, 4 capacitors in the 4 kJ units have failed at 41,000 234,000, 298,000, and 343,000 pulses respectively. Five capacitors now have over 200,000 pulses and three over 350,000 pulses and are still operating satisfactorily.

This study has evolved the components for a 4 kJ 40 kV, lightweight, high-mean-power PFN for use in a burst mode at 125 pps. The inductors are simple helical coils of copper tubing. The plastic-cased capacitors have been designed specifically for high-mean-power density in burst mode and have expected lives - 10^6 shots at 65°C with an energy density of 19 J/kg. The finished 4 kJ unit weights 50 kg.

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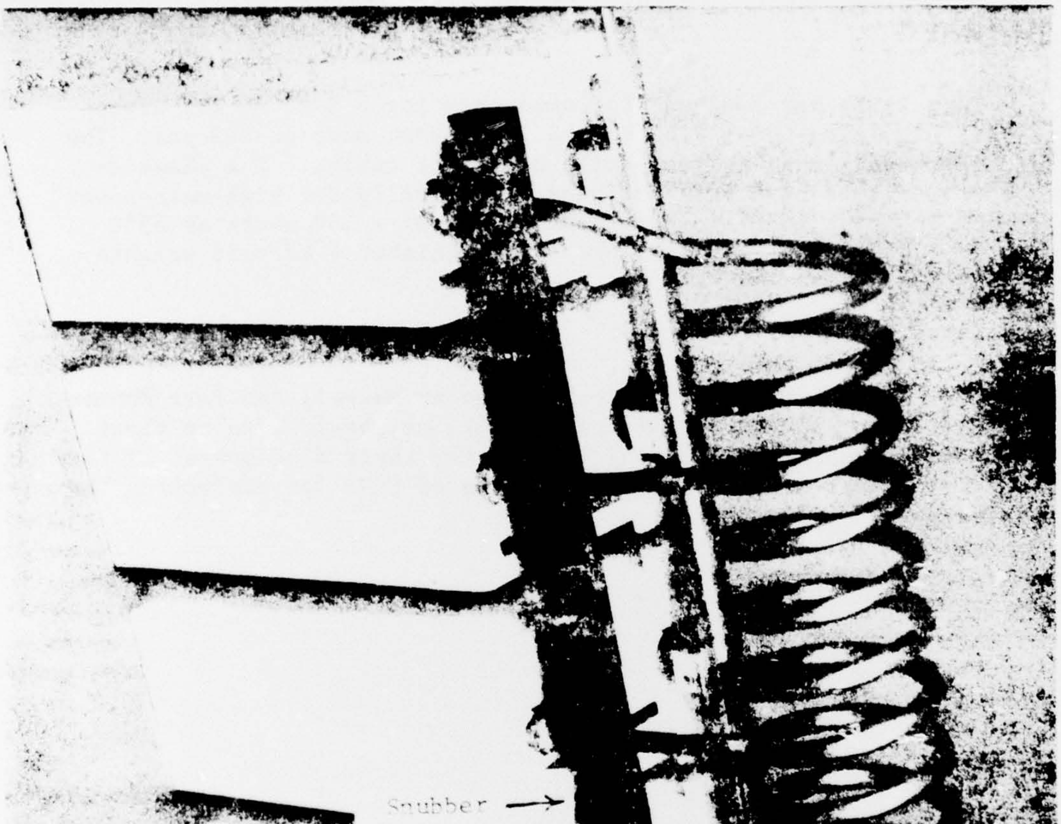

Figure 1. 4 Kilojoule PFN